North American carbon dioxide sources and sinks: magnitude, attribution, and uncertainty

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North America is both a source and sink of atmospheric carbon dioxide (CO_2). Continental sources – such as fossil-fuel combustion in the US and deforestation in Mexico – and sinks – including most ecosystems, and particularly secondary forests – add and remove CO_2 from the atmosphere, respectively. Photosynthesis converts CO_2 into carbon as biomass, which is stored in vegetation, soils, and wood products. However, ecosystem sinks compensate for only ~35% of the continent's fossil-fuel-based CO_2 emissions; North America therefore represents a net CO_2 source. Estimating the magnitude of ecosystem sinks, even though the calculation is confounded by uncertainty as a result of individual inventory- and model-based alternatives, has improved through the use of a combined approach.

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Carbon dioxide (CO_2) is globally the single most important greenhouse gas (GHG) released to the atmosphere by human activities (IPCC 2007). In 2005, the contribution of CO_2 to global radiative forcing, a measure of influence on Earth's radiation budget and an index of importance as a climate-change mechanism, was larger than that of all other long-lived anthropogenic GHGs combined (IPCC 2007). The global radiative forcing from anthropogenic CO_2 sources was approximately equivalent to the total *net* anthropogenic radiative forcing. Since at least 1950 and until circa 2006, when it was surpassed by China, the US had the highest anthropogenic CO_2 emissions by country, from the combustion of fossil fuels and the production of cement (Gregg *et al.* 2008). Accordingly, along with contributions from Canada and Mexico (the countries with the seventh and 11th highest emissions of fossil-fuel-based CO_2, respectively, for 2003–2008; Boden *et al.* 2011), North America has long been, and has long been known to be, a *source* of atmospheric CO_2 and a major contributor to the well-documented increase of CO_2 in the atmosphere. This has important implications for anthropogenic global warming and future climate change (Field *et al.* 2007; IPCC 2007).

In a nutshell:

- North America is currently a net source of atmospheric carbon dioxide (CO_2); in the first 5 years of the 21st century, continental ecosystems annually absorbed the equivalent of only ~35% of the CO_2 from North American fossil-fuel emissions, a source-to-sink ratio of nearly 3:1
- Regrowing forests account for between 30% and 70% of the North American terrestrial sink for atmospheric CO_2
- Uncertainties in estimates of the size of the North American CO_2 sink remain high (about ± 50–80%); much of this uncertainty is associated with ecosystems (eg shrublands) that are excluded from forest and cropland inventories
- Despite the high uncertainty associated with individual approaches, synthesis across alternatives yields more robust estimates of uncertainty (about ± 25%)

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Although the presence of a global Northern Hemisphere *sink* for atmospheric CO_2 is well described (Denman *et al.* 2007; Field *et al.* 2007), the contribution of North America to that sink is less certain. The mass balance of CO_2 in the atmosphere virtually necessitates that ~30% of the CO_2 released as global anthropogenic emissions is taken up by and stored in terrestrial ecosystems around the world (Canadell *et al.* 2007). This terrestrial sink is thought to be located predominantly in the Northern Hemisphere (Denman *et al.* 2007), yet its magnitude – as well as the relative contributions of North America and Eurasia – is unknown (see references in Butler *et al.* 2010; Williams *et al.* 2012). For instance, specific components of the terrestrial sink include growing forests, aggrading peatlands (the accumulation of soil organic matter), and agricultural systems deliberately managed to enhance soil carbon (C) retention and storage. The current magnitude of these particular sinks is also not well quantified. As a result, the magnitude of the *net* source of atmospheric CO_2 from North America is not nearly as well known as that of the *gross* source from fossil-fuel emissions. Additional uncertainty surrounds the contribution of CO_2 emissions from less-well-known sources, including deforestation, fire, and other disturbances, and the sinks associated with post-disturbance recovery. Quantifying the current sizes of North

American CO_2 sources and sinks is further confounded by uncertainties regarding how biogenic processes, interacting in aggregate at ecosystem and landscape levels, respond to variations in climate over time and at large spatial scales. This latter uncertainty is amplified in projections of future sources and sinks in the face of a changing climate (for further discussion, see Luo and Weng 2011).

In 2007, the first State of the Carbon Cycle Report (SOCCR) – one of the US Climate Change Science Program's synthesis and assessment products (CCSP 2007; King *et al.* 2007) – concluded that, circa 2003, vegetation in North America annually removed the equivalent of ~30% of the continent's fossil-fuel-based atmospheric CO_2 emissions. One-half of that North American terrestrial sink was attributed to regrowth of forests in the US on former (decades-old) agricultural land and on timberland recovering from commercial harvest (King *et al.* 2007). The SOCCR also concluded that the North American sink accounted for perhaps 25% of the global terrestrial sink. However, the SOCCR's estimate of the extent of the North American sink was highly uncertain.

Here, we assess the balance of CO_2 sources and sinks in North America for the first decade of the 21st century. This assessment is a revision of the SOCCR's synthesis and assessment, based on revised estimates that used subsequently available research (mostly results from the North American Carbon Program; NACP). The NACP is a multi-agency multidisciplinary research program, with the goal of developing a scientific understanding of North America's C sources and sinks (Wofsy and Harris 2002; Denning *et al.* 2005; NACP 2012). Estimates of forest and cropland CO_2 sink magnitudes have been revised based on analyses of C stock inventories; we incorporate model estimates of the North American CO_2 exchange with the atmosphere that were not used in the SOCCR. We also include a more explicit consideration of land-use change, fire, and the lateral movement or spatial redistribution of C-containing products. Our assessment is not a comprehensive review of recent literature on C cycling in North America but rather a synthesis of syntheses of continental-scale CO_2 exchange with the atmosphere; this "meta-synthesis" updates the net balance of sinks relative to the fossil-fuel source. We also investigate the consequences of the NACP syntheses for uncertainty in the North American CO_2 sink, but we do not consider the uncertainty derived from methods of characterizing specific sources of uncertainty, including sampling error in inventories and probabilistic approaches to model parameters. Instead, we focus on one measure of uncertainty – the *aggregate* uncertainty reflected in differences among estimates in the magnitude of the North American sink. These differences include various sources of uncertainty, such as variability in the choice of parameter values among models, as well as structural uncertainties (eg differences in functional representations or processes included in or absent from different models).

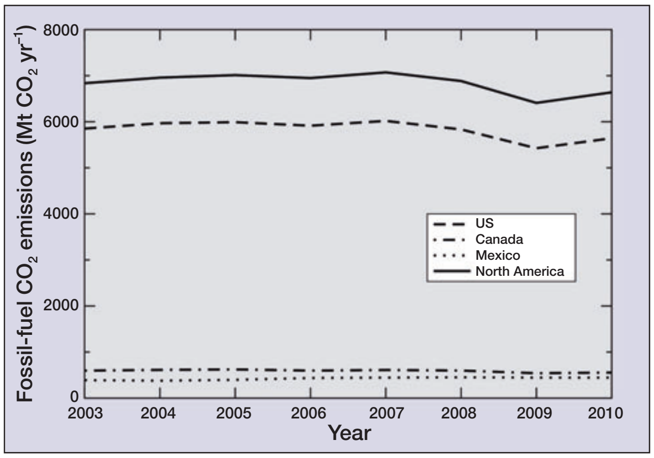

Figure 1. *Fossil-fuel emissions from North America, 2003–2010.*

Table 1. North American fossil-fuel emissions (Mt CO_2) in 2003 and 2010

	2003		*2010*[‡]	*Percent change (2003 to 2010)*
	SOCCR[*]	Revised[†]		
North America	6805	6838 (+0.5%)	6649	–2.8
US	5800	5851 (+9.0%)	5651	–3.4
Canada	601	597 (–0.7%)	554	–7.2
Mexico	403	390 (–3.2%)	443	+13.6

Notes: [*]Pacala *et al.* (2007), originally reported in units of Mt C, using US Energy Information Agency (EIA) online data for 2003 that were posted in 2005. [†]Revised (EIA 2009); numbers in parentheses depict the percent change from SOCCR estimates. [‡]2010 emissions from Canada and Mexico are not available from the Energy Information Administration for direct comparison with the estimates for 2003; accordingly, relative increases from 2009 to 2010 for the US, Canada, and Mexico from the Carbon Dioxide Information Center analysis (Peters *et al.* 2012) were applied to the respective 2009 estimates from EIA (2009).

Sources of CO_2

Fossil-fuel combustion

In North America, the primary source of CO_2 to the atmosphere is from fossil fuels (emissions from the combustion of petroleum, natural gas, and coal), which, according to the SOCCR, totaled 6805 megatons (Mt) of CO_2 in 2003 (Pacala *et al.* 2007). The US, Canada, and Mexico contributed approximately 85%, 9%, and 6%, respectively, of the North American total (Table 1). Fossil-fuel CO_2 emissions from the US and from North America as a whole increased after 2003, peaked in 2007, and then declined in 2008 and more precipitously in 2009 (Figure 1). The decline was a consequence of the economic downturn from December 2007 to June 2009 (NBER 2010) with the accompanying decline in electricity generation and reduced consumption of petroleum and coal by the industrial and transportation sectors (EIA 2009, 2010). In 2010, fossil-fuel CO_2 emissions from the US increased sharply, by almost 4% as compared with emissions in 2009 (Figure 1; EIA 2011).

This increase was largely due to the growth in industrial energy consumption accompanying the rebound in the economy, with contributions from increases in electricity demand (Boden and Blasing 2011; EIA 2011). Fossil-fuel CO_2 emissions from Canada underwent a related but smaller rebound (up 2.4% from 2009), while those from Mexico were essentially unchanged (Boden and Blasing 2011). Altogether, North American fossil-fuel CO_2 emissions were 6649 Mt CO_2 in 2010 (Figure 1; Table 1), a decrease of 2.3% from 2003 as a consequence of the reduced economic activity in 2008 and 2009. A simple extrapolation of the trend from 2003 to 2007 suggests that, in the absence of the economic downturn, fossil-fuel CO_2 emissions from North America would have exceeded 7000 Mt CO_2 in 2010.

The uncertainty in North American fossil-fuel emissions – as recorded in the SOCCR – was equivalent to ±10%, the relative range within which, with high (95%) certainty, the actual quantity is judged to lie. The SOCCR authors concluded, for example, that fossil-fuel emissions from North America likely ranged from 6124 to 7486 Mt CO_2 yr^{-1} (6805 ± 10%) in 2003. Subsequent analysis for the US, Canada, and Mexico yielded less uncertainty for total North American emissions (approximately ±4%; R Andres, pers comm). Thus, fossil-fuel emissions from North America were probably in the region of 6383 to 6915 Mt CO_2 (6649 ± 266 Mt CO_2 yr^{-1}) in 2010.

Land-use change and disturbance

Anthropogenic land-use changes (including deforestation, reforestation, and afforestation) and natural disturbances (such as wildfire, insect outbreaks, and storms) can represent either net sources or net sinks of CO_2 (eg Amiro *et al.* 2010; Liu *et al.* 2011), and often change from one to the other over time. The complexity and spatio–temporal heterogeneity of immediate, longer-term, and legacy effects of land-use changes complicate efforts to quantify their net exchange of CO_2 with the atmosphere. The impacts of land-use change and other disturbances on C stored in vegetation and soil contribute to the changes in C stocks used in inventory-based GHG accounting (eg Heath *et al.* 2011); however, land-use changes and disturbances cannot be explicitly separated from all the other changes (Hayes *et al.* 2012). Moreover, because these inventories record changes in C stocks but not necessarily the cause of those changes, it is difficult to ascertain the relative contribution of land-use changes and disturbances to emission levels. Nevertheless, land-use changes and disturbances are believed to have produced legacy sinks that generally exceeded sources within the contemporary North American land-based C budget (Myneni *et al.* 2001; Goodale *et al.* 2002; King *et al.* 2007). This net sink has been associated in particular with the recovery from past forest harvest and reforestation of abandoned cropland.

As a result of ongoing deforestation, Mexico is an exception to this trend; as indicated in the SOCCR, ~190 ± 190 Mt CO_2 yr^{-1} were released during the 1980s from Mexican forests, acting as an emissions source. According to de Jong *et al.* (2010), land-use change in Mexico between 1993 and 2002 resulted in lower net emissions (86.9 ± 34.4 Mt CO_2 yr^{-1}). Over that time period, biomass recovery in reforestation and afforestation offset only ~13% of the gross CO_2 emitted from deforestation in Mexico.

Wildfire and other biomass burning events across North America are major drivers of the continental-scale C budget (Kurz and Apps 1999; van der Werf 2010). Using inventory-based methodology, Stinson *et al.* (2011) estimated fire-related emissions for Canada's managed forest area at 78 Mt CO_2 yr^{-1} for the 1990s and at 74 Mt CO_2 yr^{-1} between 2000 and 2008. In Canada, nationwide fire-related emissions derived from process-based model estimates, including non-managed forests, indicate that emission levels were ~118 Mt CO_2 yr^{-1} for both the 1990–1999 and 2000–2006 time periods (Hayes *et al.* 2011). By way of comparison, in the conterminous US, inventory-based estimates suggest an increase in direct wildfire emissions from 60–75 Mt CO_2 yr^{-1} in the 1990s to 140–173 Mt CO_2 yr^{-1} in the 2000s, with an estimated additional 24 Mt CO_2 yr^{-1} emitted from prescribed burning in the latter decade (Heath *et al.* 2011; US EPA 2012). Model-based estimates suggest that emissions from wildfires in the non-inventoried lands of Alaska nearly doubled, from 44 Mt CO_2 yr^{-1} in the 1990s to 84 Mt CO_2 yr^{-1} between 2000 and 2006 (Hayes *et al.* 2011). The C-accounting methodology used by de Jong *et al.* (2010) excluded wildfire emissions estimates but calculated 31 Mt CO_2 yr^{-1} direct emissions from biomass burning associated with forest conversion in Mexico from 1993 to 2002. Relative to emissions from burning forests, much lower emissions are associated with agricultural burning in croplands; McCarty (2011) estimated 6.1 Mt CO_2 yr^{-1} in emissions from the burning of crop residue in the US between 2003 and 2007.

Aside from fire-related emissions estimates, studies on the C budget impacts of other natural disturbances are few and are largely site- and/or event-based (eg Chambers *et al.* 2007; Brown *et al.* 2010). However, agents associated with such disturbances (eg insect outbreaks and storms) have spatial extents similar to those affected by wildfire, and studies suggest that their C impacts can be substantial (eg Kurz *et al.* 2008; Edburg *et al.* 2011). Yet these disturbances differ from fire in that they do not result in direct CO_2 emissions but rather that they trigger the transfer of live vegetation biomass to dead organic matter stocks, which emit CO_2 to the atmosphere more slowly as a result of decay over time following the disturbance. For example, Zeng *et al.* (2009) estimated the average transfer of C to dead organic matter – from tree biomass killed by hurricane- and tropical storm-related impacts in the US – to be equivalent to ~53 Mt CO_2 yr^{-1}

between 1851 and 2000. Inventory-based estimates for Canada indicate that the transfer of C to dead organic matter as a result of insect-killed trees increased from 1.7 Mt C yr^{-1} in the 1990s to 51.8 Mt C yr^{-1} between 2000 and 2008, primarily driven by a mountain pine beetle outbreak in British Columbia (Stinson *et al.* 2011). National statistics on insect outbreaks and impacts are unavailable from inventory programs in the US and Mexico.

Sinks of CO_2

Approximately 30% of North American fossil-fuel emissions in 2003 were offset by an aggregate continental sink of 1852 Mt CO_2 yr^{-1} associated with terrestrial biogeochemistry and ecology (Table 2; King *et al.* 2007; Pacala *et al.* 2007). This estimate was derived exclusively from inventory-based methods in which the total amount of C in a pool (eg living forest trees plus forest soils) is measured on two separate occasions; an observed difference between the two measurements indicates whether the pool gained or lost C over the time interval. Translating inventories of C stock changes into atmospheric CO_2 sources and sinks requires additional information on the form and fate of those gains and losses. Figure 2 illustrates the conceptual approach used by Hayes *et al.* (2012) to estimate net ecosystem exchange (NEE), or the vertical exchange of CO_2 between the surface and the atmosphere (see Chapin *et al.* 2006), from inventory-based information. A negative value of NEE signifies a removal of atmospheric CO_2, a land-based sink. By definition, NEE considers only vertical CO_2 exchange. Comprehensive analysis must also account for lateral or horizontal transport into and out of the system (eg export of wood or agricultural products), thereby allowing C gain to be equated with a regional sink for atmospheric C and C loss with a regional source (Goodale *et al.* 2002; Pan *et al.* 2011; West *et al.* 2011; Hayes *et al.* 2012). Translating the C source to CO_2 source requires either the assumption that, at least approximately, all or most of the C was lost as CO_2 (as opposed to a different gas, such as methane), or the application of emission factors like those used in estimating GHG emissions from forest fires or biomass burning (Heath *et al.* 2011; Stinson *et al.* 2011). Translating the C sink to CO_2 is a more straightforward stoichiometry because C uptake from the atmosphere is limited to CO_2 uptake via photosynthesis.

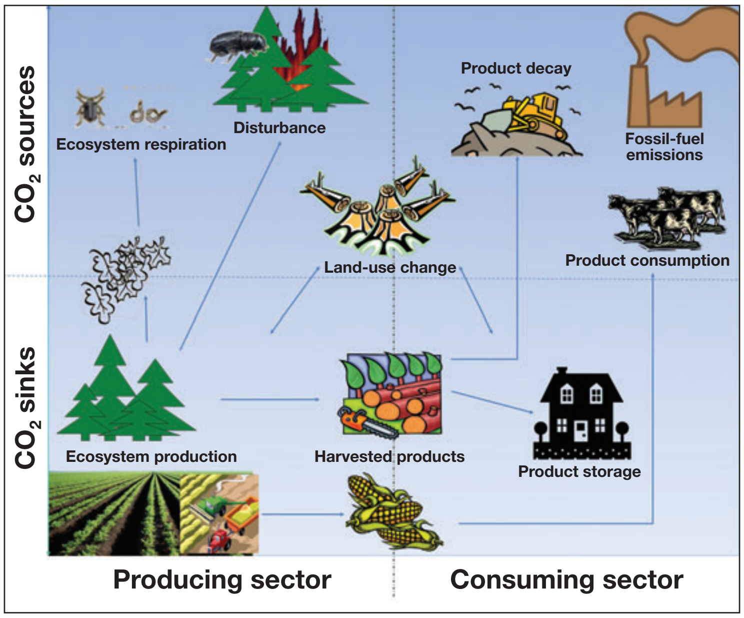

Figure 2. *Conceptual diagram of the North American CO_2 budget: sources, sinks, and lateral movement.*

Hayes *et al.* (2012) synthesized inventory-based C budgets for North American forest, cropland, and other lands. The resulting estimate of the aggregate continental sink, averaged for the period 2000–2006, is only 65% of the SOCCR estimate (Table 2). However, the latter estimate included "additional fluxes" (ie a large and highly uncertain sink associated with woody encroachment, wetland sinks, and sequestration in rivers and reservoirs) that were excluded from the former analysis. An estimate based on the inventories alone (such as that by Hayes *et al.* 2012) is only a partial approximation of the North American sink, albeit the better known, less uncertain part. A more complete estimate (and comparison with model-based estimates) requires inclusion of these additional fluxes. By adding these additional fluxes to the inventory-only estimate of Hayes *et al.* (2012), the revised aggregate continental sink is 12% higher than the SOCCR estimate (Table 2). The Hayes *et al.* (2012) estimates are,

Table 2. North American CO_2 (Mt CO_2 yr^{-1}) sources (positive values) and sinks (negative values) of the early 21st century

Source (positive) or sink (negative)	*US*	*Canada*	*Mexico*	*North America*
Fossil fuel	5651	554	443	6649
Ecosystem sources (positive) or sinks (negative)	*US*	*Canada*	*Mexico*	*North America*
SOCCR (Pacala *et al.* 2007)	–1793	–235	176	–1852
Hayes *et al.* (2012), inventory-based	–1107	–160	67	–1199
Hayes *et al* (2012), with "additional fluxes"	na	na	na	–2076
Hayes *et al.* (2012), AIM ensemble	–2512	–871	–32	–3415
Hayes *et al.* (2012), TBM ensemble	–1309	–457	–106	–1873
Huntzinger *et al.* (2012), TBM (prognostic)	–733	–367	*	–1467
Huntzinger *et al.* (2012), TBM (diagnostic)	–2567	–367	*	–3300

Notes: na = estimate not available; * = estimate for that country is not available, but the country's contribution is included in the estimate for North America.

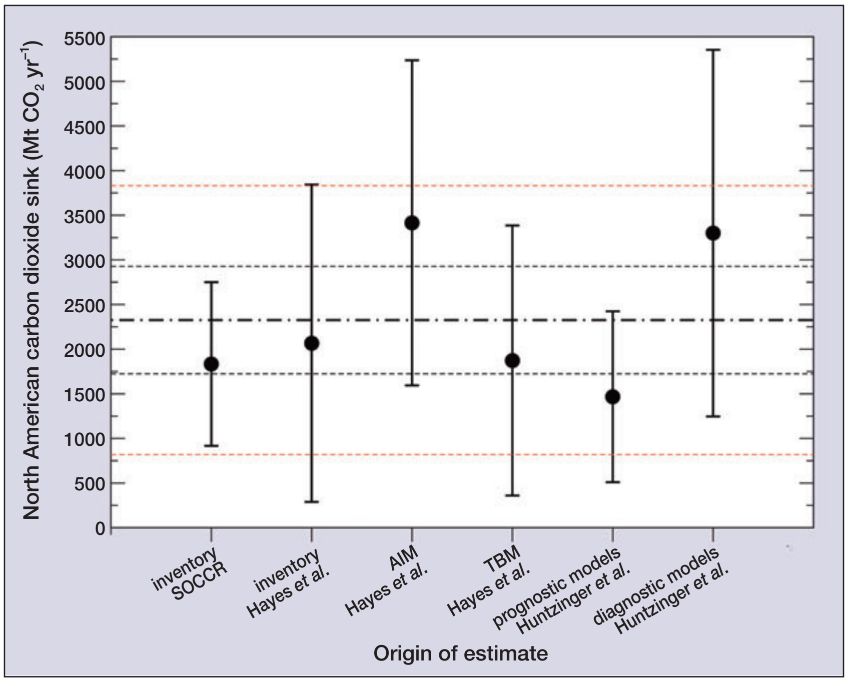

Figure 3. *The North American CO_2 sink, circa 2000–2005, as estimated by C inventory analysis, atmospheric inversion models (AIM), and terrestrial biosphere models (TBM). Solid circles mark the mean value of the individual approaches. Error bars indicate the range that is very likely to include (with 95% confidence) the actual value. The black broken (dot–dash) line indicates the average of the mean estimates; the surrounding black dashed line is the 95% confidence interval. The red dashed lines indicate the averages of the upper and lower bounds on the individual estimates.*

nevertheless, within 917–2150 Mt CO_2 yr^{-1}, the range that – according to the SOCCR authors – bounded the actual value of the North American sink (Figure 3).

Inclusion of the additional fluxes increased the uncertainty of the estimated North American sink from ±77% to ±86% (Hayes *et al.* 2012). The latter is greater than the sink's uncertainty estimated by the SOCCR (±50%). The increase in uncertainty when including the additional fluxes occurs despite the Hayes *et al.* (2012) reduction in uncertainty in the inventory-based estimate of the forestland sink to ±41% compared to ±50% (by Pacala *et al.* [2007] and the SOCCR).

Alternative, non-inventory-based assessments of the contemporary North American C budget have been performed through model–model and model–data comparisons, as part of the NACP's regional and continental interim-synthesis (RCIS; Hayes *et al.* 2012; Huntzinger *et al.* 2012). The RCIS used "off-the-shelf" model simulations – including two alternative modeling approaches – from analyses completed by NACP projects and other recently published studies. One method used atmospheric inversion models (AIM) in a top-down approach to infer land-based CO_2 sources and sinks based on atmospheric transport modeling constrained by measurements of CO_2 concentration from observational networks. The other method uses terrestrial biosphere models (TBM) in a bottom-up approach to estimate the land–atmosphere exchange of C based on simulating biogeochemical processes driven by climate, atmospheric chemistry, and land surface factors.

The mean continental-scale NEE estimates from the AIM and TBM ensembles (–3415 and –1873 Mt CO_2 yr^{-1}, respectively) by Hayes *et al.* (2012) were both larger than the inventory-based estimate excluding the additional fluxes (–1199 Mt CO_2 yr^{-1}) estimated by Hayes *et al.* (2012). However, these additional fluxes are, in principle, included in the model simulations, particularly those from the AIM. Accordingly, it is more appropriate to compare the AIM and TBM ensembles with the inventory-based estimate that includes the additional fluxes (–876 Mt CO_2 yr^{-1}). The correspondingly larger inventory-based sink estimate agrees more closely with the model estimates, especially those from the TBM (Table 2; Figure 3). The study also reports large variability across the model estimates, with the standard deviation representing 72% and 143% of the AIM and TBM ensemble means, respectively.

Huntzinger *et al.* (2012) compared estimates of net ecosystem productivity (NEP) from the TBM of the RCIS. The NEP from these simulations is conceptually similar, although not identical, to the NEE of Hayes *et al.* (2012) (see Chapin *et al.* 2006). In the analysis by Huntzinger *et al.* (2012), prognostic TBM were distinguished from diagnostic TBM; diagnostic models differed from prognostic models primarily in the former's use of satellite-derived leaf area index (see Huntzinger *et al.* 2012). As a group, the diagnostic models generated a larger estimate of the North American sink than the prognostic models' estimate (Table 2; Figure 3). Similar to Hayes *et al.* (2012), Huntzinger *et al.* (2012) found wide variability across models. Estimates of mean North American NEP for the period 2000–2005 varied between a source of 2567 Mt CO_2 yr^{-1} and a sink of 6233 Mt CO_2 yr^{-1} (for prognostic models) and between a source of 1100 Mt CO_2 yr^{-1} and a sink of 8067 Mt CO_2 yr^{-1} (for diagnostic models). The range in the models' estimates appears to be driven by a combination of factors, including the representation of photosynthesis, differences in environmental driver data, and whether nutrient limitation is considered in soil C decomposition.

The model-based estimates of the NACP RCIS concur, at least in the ensemble means, with the inventory-based estimates that North America was a CO_2 sink, as opposed to a CO_2 source, in the early years of the 21st century (Figure 3). The magnitude of that sink is less certain. The mean value generated by the TBM ensemble of Hayes *et al.* (2012) is very similar to the SOCCR's mean estimate

(Pacala *et al.* 2007), whereas the mean of the prognostic TBM of Huntzinger *et al.* (2012) is slightly lower. The means produced by Hayes *et al.*'s (2012) TBM ensemble and Pacala *et al.*'s (2007) SOCCR estimate are both lower than Hayes *et al.*'s (2012) inventory-based mean estimate after correcting for additional fluxes (which, as previously stated, are in principle included in the model estimates). However, the Hayes *et al.* (2012) TBM-ensemble and the Pacala *et al.* (2007) estimates both lie well within the ranges derived from analyses of inventory data, ranges that are very likely to include the actual flux (Figure 3). In contrast, the means produced by the AIM and the diagnostic TBM estimates are larger than the means of inventory-based estimates from Pacala *et al.* (2007) and Hayes *et al.* (2012; Figure 3). They also lie outside the range of high confidence as reported in the SOCCR, but fall within the larger inventory-based range of Hayes *et al.* (2012) when including the Hayes *et al.* (2012) additional fluxes (Figure 3).

Large estimates of the North American CO_2 sink's magnitude are a characteristic and persistent feature of analyses with AIM and might be overestimates, with biases rooted in the inversion methodology (Stephens *et al.* 2007; Hayes *et al.* 2012). The similarity between results from the AIM and the diagnostic TBM is at least suggestive that this is a bias shared with diagnostic terrestrial ecosystem modeling. On the other hand, important sinks are also possibly being overlooked in the bottom-up inventories and by at least the prognostic TBM, resulting in an underestimate of the size of the North American CO_2 sink.

As noted above, considerable variability exists among the models in the NACP RCIS analyses. By calculating the standard error of the NACP RCIS model ensembles from Hayes *et al.* (2012) and Huntzinger *et al.* (2012) and putting aside questions regarding the distribution of model results, we can compute 95% confidence intervals for the model results (Figure 3). The lower limits on the resulting ranges are still indicative of North America being a CO_2 sink and are no smaller than the lower end of the range from the inventory-based analysis of Hayes *et al.* (2012), which very likely includes the actual magnitude of the North American CO_2 sink for the beginning of the 21st century.

Considering each of the alternative estimates individually, it seems likely that the continental-scale sink may currently be as small as 290 Mt CO_2 yr^{-1} or as large as 5350 Mt CO_2 yr^{-1} (Figure 3). However, the mean estimate of a model ensemble often agrees better with observations than with any single model (eg Lambert and Boer 2001; Schwalm *et al.* 2010), and the overlap in results from alternative, largely independent approaches is a measure of robustness (Parker 2011). Accordingly, the average of the means of the alternative estimates provides an estimate of the North American CO_2 sink synthesized across approaches. That estimate for the early 21st century is 2326 Mt CO_2 yr^{-1} (Figure 3), with associated uncertainty, measured by the 95% confidence limits, equivalent to approximately ±26%. Thus, at the beginning of the 21st century, the ecosystems of North America were very likely a sink for atmospheric CO_2 somewhere in the range of 1721 to 2931 Mt CO_2 yr^{-1} (2326 ± 605 Mt CO_2 yr^{-1}). The median value is equal to 35% of fossil-fuel emissions from North America in 2010 (cf 30% of 2003 fossil-fuel emissions reported by the SOCCR). The lower and upper ends of the range are equal to 26% and 44%, respectively, of 2010 fossil-fuel emissions.

The aggregate continental North American CO_2 sink includes contributions from various ecosystem types, sectors, and regions, some of which are associated with greater certainty and have relatively well-known contributions to the North American CO_2 sink. The inventory-based and model-based estimates agreed, for example, that US forests are the single largest contributor to the net North American CO_2 sink (King *et al.* 2007; Pacala *et al.* 2007; Hayes *et al.* 2012). Other ecosystem types, sectors, and regions are less well known and contribute further uncertainty at the continental scale. We consider these contributions in WebPanel 1, ordered according to the certainty or confidence in their contribution to the aggregate North American CO_2 sink.

■ Net CO_2 exchange with the atmosphere

Net atmospheric CO_2 emissions from North America are a result of vertical exchanges from sources and sinks and the horizontal transfer of C into and out of the region (Figure 2). Some of the C horizontally distributed within the region is stored long term (eg forest products), while some is emitted to the atmosphere within 1 to 2 years (eg agricultural products). Carbon dioxide fluxes and C imports and exports in CO_2 equivalents by sector or ecosystem are summarized in Figure 4. Our accounting considers only fluxes to and from the atmosphere, regardless of where the C is transported and emitted. Assuming the mean continental CO_2 sink for the first 5–6 years of the 21st century (estimated at 2326 ± 605 Mt CO_2 yr^{-1}) persisted through the end of the decade, net CO_2 emissions from North America in 2010 were ~4320 Mt. The fossil-fuel emissions source exceeded the total continental ecosystem sink by a factor of nearly three. Fossil-fuel emissions exceeded the largest individual sink (recovering forests) by a factor of nearly six (Figure 4).

■ Conclusions

Currently, North America is acting as a net source of CO_2 to the atmosphere. For each year between 2000 and 2005, the terrestrial ecosystems of North America absorbed the equivalent of ~35% of North America's fossil-fuel-based CO_2 emissions, representing a source-to-sink ratio of nearly 3:1. Fossil-fuel-based emissions (6649 ± 266 Mt CO_2 in 2010) dominate the continent's CO_2 source–sink budget (Figure 4). Forest regrowth in the US is responsible for 30–70% of the North American CO_2 sink. That the terrestrial ecosystems of North America have in recent years acted as a sink for atmospheric CO_2 is practically undeniable; it is the mag-

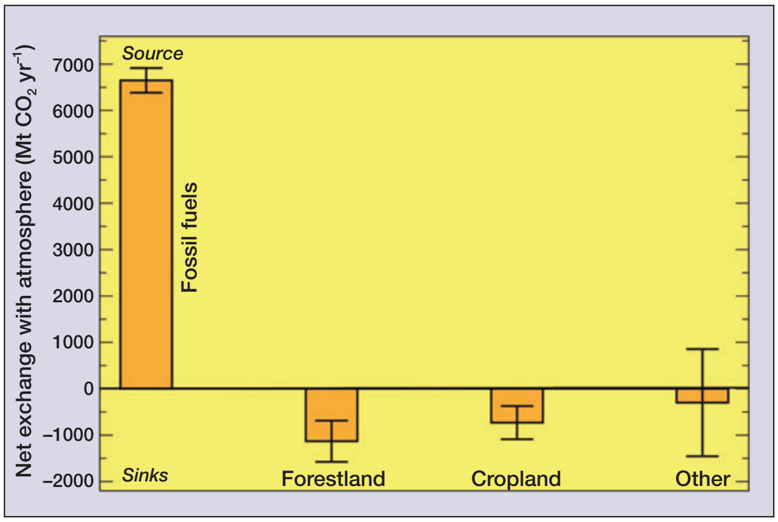

***Figure 4.** North American CO_2 sources and sinks, circa 2010. The fossil-fuel flux for 2010 was derived from this synthesis (the best estimate with a range of uncertainty that very likely, with 95% confidence, includes the actual flux). Sink estimates (mean and 95% confidence intervals) are averages including both model- and inventory-based estimates from Hayes* et al. *(2012). Note that the model-based estimates for Other (non-forest, non-cropland) in Hayes* et al. *(2012) are sinks of CO_2, whereas in the inventory-based estimate, Other is a source. The mean of these two estimates is a sink, as indicated by the orange bar, but the uncertainty surrounding this mean allows for the possibility that Other is actually a source (ie the uncertainty bars extend into the source region). Other is a source in the inventory-based estimate, largely because in that accounting CO_2 taken up in the Forestland and Cropland sinks is released to the atmosphere from Other lands, as the wood and agricultural products are consumed and decomposed in, for example, urban (ie Other) lands (see Figure 2 and main text).*

nitude of this sink that remains uncertain. Overall, the SOCCR's conclusion that the actual value of the aggregate North American CO_2–C sink was likely (with 95% confidence) to be within ±50% of the reported value remains a reasonable conservative estimate. More recent inventory-based estimates, such as those used in the SOCCR, have reduced uncertainty in components of the North American CO_2 sink, specifically the contribution of forests. On the other hand, variability among model-based estimates from both top-down atmospheric inversion models and bottom-up ecosystem process-based models is high, with uncertainties ranging between ±50–80%. Resolution of uncertainty and reconciliation of alternative estimates are ongoing efforts. Nonetheless, synthesis across alternative estimates provides an approximation – for the first decade of the 21st century – of the North American CO_2 sink (2326 ± 605 Mt CO_2 yr^{-1}), which is 25% higher than the SOCCR estimate and is associated with less relative uncertainty (±25%).

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